giving the citron spectrum, and no sooner had the exquisite sensitiveness of this spectrum test forced itself on my notice than I sought for yttrium in other minerals. The facts which I had noticed in connexion with the variation of the appearance of the citron spectrum, according to the quantity of yttrium present, showed that it might be possible to devise a process for the rough quantitative estimation of yttrium, and after several experiments a spectrum test was devised sufficiently delicate to detect one-millionth part of yttria in a mineral. A table is given showing the results of this quantitative spectrum analysis, from which it is seen that amongst other substances a specimen of coral contains one part of yttrium in 200 parts; strontianite, one part of yttrium in 500 parts; chondrodite, from Mount Somma, one part in 4,000; calcite, one part in 10,000; ox bone, one part in 10,000; an earthy meteorite (Alfianello), one part in 100,000; and tobacco ash, one part in 1,000,000.

The following Paper was read:—

"Experiments upon the Heart of the Dog with reference to the Maximum Volume of Blood sent out by the Left Ventricle in a Single Beat, and the Influence of Variations in Venous Pressure, Arterial Pressure, and Pulse Rate upon the Work done by the Heart." By WILLIAM H. HOWELL, A.B., Fellow of the Johns Hopkins University, and F. DONALDSON, Jr., A.B. Communicated by Dr. M. FOSTER, Sec. R.S.

(Abstract.)

Owing to the indirectness of the methods hitherto used for estimating the quantity of blood pumped out from the left ventricle at each systole, this important factor in all calculations of the work done by the heart has never been satisfactorily determined. Of the later physiologists who have investigated the subject, Volkmann and afterwards Vierordt, from calculations based upon the mean velocity of the stream of blood in the unbranched aorta, obtained the fraction $\frac{1}{400}$ as representing the ratio of the average weight of blood ejected at each systole of the left ventricle to the weight of the whole body. Fick, from data obtained by placing the arm in a plethysmograph, and estimating the velocity of the stream of blood in the axillary artery from the increase in volume of the whole arm at each systole of the heart, arrived at a much smaller fraction, about $\frac{1}{1000}$, for the ratio between the weight of blood thrown out at each systole and the body-weight.

At the suggestion of Professor Martin, and under his directions, we undertook some experiments upon this subject, making use of his method of isolating the heart. The quantity of blood ejected from the left ventricle at each systole under varying conditions of venous pressure, arterial pressure, and pulse-rate, can be determined directly with this method by catching the blood as it is pumped out from the tube connected with the aorta of the dog. In all the observations made the blood was collected during a period of 30 seconds, and the quantity thus obtained divided by the number of heart beats occurring during that time, as shown on the kymograph, in order to determine the quantity pumped out at each systole. The results of our work fall under four different heads.

I. *The Maximum Quantity of Blood which can be thrown out from the Left Ventricle at a single Systole.*

The method of working in determining this quantity was to increase the amount of blood flowing into the right side of the heart, by raising the supply flask connected with the superior vena cava, until a limit was reached in the amount of blood pumped out from the left ventricle, *i.e.*, a point beyond which increase of the pressure and the quantity of the blood flowing into the right side of the heart caused no increase in the quantity of the blood sent out from the left ventricle.

The main result of these experiments may be stated at follows: With a mean pulse-rate of 180 per minute in the dog, the mean ratio of the maximum weight of blood pumped out from the left ventricle at each systole to the body-weight is $\frac{1}{855}$, or ·00117. The maximum outflow from the left heart was obtained in all cases at or below a venous pressure on the right side of 60 centims. of defibrinated calf's blood (46 millims. of mercury).

With regard to the maximum outflow from the left ventricle at the normal pulse-rate (120 per minute) of a dog, we have only one experiment to offer. According to that experiment the ratio of the maximum weight of blood pumped out from the left ventricle at each systole to the body-weight, with a pulse-rate of 120 per minute, is about $\frac{1}{700}$, or ·0014.

In applying these results to the normal dog, we believe that the average quantity of blood pumped out from the left ventricle at each systole in the living dog is approximated most nearly in our experiments by the maximum outflow; in other words, we think it probable that the left ventricle during life is distended at each diastole to about its maximum capacity. In coming to this conclusion we were influenced chiefly by three considerations. 1. The same opinion has been expressed by Royar, the result of his work on the frog's heart. 2. Calculations of the time required for a complete

circulation of the blood to take place in a normal dog, based upon the maximum quantity of blood sent out from the left heart at each systole, as determined by our experiments, give results which agree with what we would expect from the time found necessary by Vierordt from direct experiment for the jugular-femoral path. 3. It is probable that in our experiments the left heart, at the time the maximum outflow was obtained from it, worked under conditions of pressure closely resembling those to which it is subject during life. The pressure in the left auricle, with the highest venous pressure (46 millims. of mercury) used on the right side, had a maximum value of 20 millims. of mercury, a mean value of 16 millims., which is probably about what occurs during life, since Goltz and Gaule found that the maximum pressure in the right auricle of the dog is about 19·6 millims. of mercury.

Owing to the difference in pulse-rate between the dog and man, no inference can be made with any certainty from the results obtained with the dog to the case of man.

II. *Influence of Variation of Arterial Pressure on the Work done by the Heart.*

Arterial pressure was varied by raising or lowering the end of the outflow tube leading from the aorta. As the result of the experiments we can state that variation of arterial pressure from 58 to 147 millims. of mercury, have practically no direct effect whatever upon the quantity of blood sent out from the left ventricle at each systole.

Since the pulse-rate is not altered, the work done by the left ventricle, therefore, varies directly as the arterial pressure against which it works, within the limits named. For how much wider limits than those given this may hold true we have not yet determined. Since there is every reason to believe that under normal conditions the force of the systole is more than sufficient to completely empty the ventricular cavity, and we have found that with arterial pressures from 58 to 147 millims. the quantity of blood pumped out from the left ventricle at each systole remains constant, it seems probable that within these limits at least the force of the ventricular contraction is not influenced by variation in arterial pressure, but remains maximal throughout.

III. *Influence of Variation of Venous Pressure on the Work done by the Heart.*

The venous pressure on the right side was gradually increased from 10 centims. to 60 or 70 centims., and the outflow from the aorta measured for each venous pressure used. The records of these experiments show in a marked manner the influence of venous pressure on the outflow from the ventricle. As the general results of

the experiments, it was found that the outflow from the left ventricle, and consequently the work done by it, increases with the venous pressure, but not proportionally, up to the point of maximum work. It is certain that the most direct factor influencing the quantity of blood sent out from the ventricle is the intra-ventricular pressure by which it is distended during diastole. Leaving out the aspirating action of the thorax, the intra-ventricular pressure during life must be mainly owing to the action of the auricles, since the pressure in the great vein emptying into the auricles probably never rises to any important positive value, indeed, according to the experiments of most observers, has a mean negative value. The contraction of the auricles then must have the most important and direct effect upon the work done by the ventricles.

IV. *Influence of Rate of Beat on the Work done by the Heart.*

The rate of beat of the heart was varied in these experiments by heating or cooling the blood supplied to it. In this way the pulse-rate was changed in one case from 228 to 77 beats in a minute, and back again to 140 in a minute, in another case from 204 to 65·5, and back again to 157, and so on. The general result may be stated as follows:—A diminution of pulse-rate, brought about by lowering the temperature of the blood flowing into the heart, causes an increase in the quantity of blood thrown out from the ventricle at each systole, and consequently an increase in the work done at each systole, and *vice versâ*. The changes in the outflow from the ventricle at each systole are not, however, inversely proportional to the changes in the pulse-rate. The total outflow and the total work done during any given period of time decreases with a diminished pulse-rate, and increases with an increased pulse-rate.